

ON TESTING THE EQUIVALENCE PRINCIPLE WITH EXTRAGALACTIC BURSTS

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ABSTRACT

An interesting test of Einstein's equivalence principle (EEP) relies on the observed lag in arrival times of photons emitted from extragalactic transient sources. Attributing the lag between photons of different energies to the gravitational potential of the Milky Way (MW), several authors derive new constraints on deviations from EEP. It is shown here that potential fluctuations from the large scale structure are at least two orders of magnitude larger than the gravitational potential of the MW. Combined with the larger distances, for sources at redshift $z \gtrsim 0.5$ the *rms* of the contribution from these fluctuations exceeds the MW by more than 4 orders of magnitude. We provide actual constraints for several objects based on a statistical calculation of the large scale fluctuations in the standard Λ CDM cosmological model.

Keywords: Cosmology: large scale structure – Gravitation

1. INTRODUCTION

Any deviation from EEP will have far reaching consequences on all fundamental theories of physics (Will 2006). The inability to distinguish between properties of motion in non-inertial frames of reference and certain gravitational fields in inertial frames (Landau & Lifshitz 1975) implies that the world line of a massless particle is independent of its energy. Delays between arrival times of different types of radiation from astronomical burst events have been proposed (Krauss & Tremaine 1988; Sivaram 1999) to constrain deviations from EEP through the effect of Shapiro (gravitational) time delay (Shapiro 1964). Recently, Gao et al and Wei et al (Gao et al. 2015; Wei et al. 2015) have applied this test to gamma-ray bursts (GRBs) and Fast Radio Bursts (FRBs) (Lorimer et al. 2007). Their strongest constraints are based on FRBs. Photons with different frequencies, ν , from these millisecond transients are observed to arrive at different times. The observed time delay (with respect to a reference frequency) follows $\Delta t_{obs} \sim \nu^{-2}$ as expected from the dispersion of radio waves propagating in an ionized medium. The dispersion measure (DM) is large, indicating sources of cosmological origin. Constraint on deviations from EEP are obtained by taking Δt_{obs} as an upper limit on the difference between Shapiro time delay for photons at two distinct frequencies.

Adopting the parametrized post-Newtonian approximation (PPN), deviations from EEP are described in terms of the parameter γ (Will 2006), where $\gamma = 1$ in

general relativity. The Shapiro time delay is then

$$t_{gra} = -\frac{1+\gamma}{c^3} \int_{r_o}^{r_e} U(\mathbf{r}(t), t) dr, \quad (1)$$

where the integration is along the path of the photon emitted at r_e and received at r_o . Gao et al and Wei et al focus on the contribution from the gravitational potential of the MW. Assuming a Keplerian potential for the MW they use corresponding shift

$$\Delta t_{gra}^{MW} = \Delta\gamma \frac{GM_{MW}}{c^3} \ln\left(\frac{d}{b}\right), \quad (2)$$

where $\Delta\gamma$ is the difference between the γ value for the two photons, M_{MW} is the mass of the MW, d is the distance to the source and b is the impact parameter of the light path with respect to the Galactic center. For $M_{MW} = 6 \times 10^{11} M_\odot$, $d = 1500$ Mpc and $b = 5$ kpc, this equation gives $\Delta t_{gra}^{MW} / \Delta\gamma = 3.5 \times 10^7$ s. One of the objects Wei et al use is FRB 110220 (Thornton et al. 2013). Since the observed time delay depends on frequency as ν^{-2} , most of the lag is due to dispersion of photons. Using the observed DM, the inferred redshift for this object is $z \sim 0.81$ (corresponding to $d = 1500$ Mpc). Taking the 1 second observed shift between arrival times of 1.5GHz and 1.2GHz photons as an upper limit on Δt_{gra} , they obtain $\Delta\gamma < 2.5 \times 10^{-8}$. Wei et al point out that this is a conservative upper limit since the 1 second time delay should mostly be sure to the dispersion of radio waves.

Wei et al argue that incorporating the gravitational potential from the large scale ($\gtrsim 10$ Mpc) structure

(hereafter, LSS) tightens the constraint, but they do not estimate this effect. The current paper assesses the contribution of the LSS potential field and shows that it should greatly exceed the local MW contribution. In generalizing Eq. (1) to cosmology we assume *i*) distances well within the horizon, *ii*) the mechanism for EEP breaking is decoupled from the cosmological background and is induced solely by spatial fluctuations of the gravitational potential, U^{LS} , resulting from the LSS distribution of matter, and *iii*) a PPN for the cosmological metric (Futamase 1988; Hwang et al. 2008) with γ appearing in the time and spatial components of the metric as $g_{00} \approx -(1 - 2\gamma U^{LS}/c^2)$ and $g_{ij} = a(t)(1 + 2\gamma U^{LS}/c^2)$ where $U^{LS} \ll c^2$ and $a(t)$ is the scale factor of the Universe. We write the shift in the arrival times of photons of two different frequencies due to the Shapiro effect as

$$\Delta t_{gra}(\hat{r}) = \frac{\Delta\gamma}{c^3} \int_{r_o}^{r_e} U^{LS}(r\hat{r}, z) a(z) dr, \quad (3)$$

where r_o and r_e are now comoving distances and $a = (1+z)^{-1}$ corresponds to a comoving distance $r(z)$, at a cosmological redshift z . This cosmological Shapiro shift may acquire negative as well as positive values since U^{LS} fluctuates around zero.

2. ORDER OF MAGNITUDE BASED ON THE OBSERVED LSS MOTIONS

The expected amplitude of LSS potential fluctuations can be found from the observed peculiar velocities (deviations from a pure Hubble flow), v_p , of galaxies. For a nearly homogeneous matter distribution at early cosmic times, linear theory provides the intuitive relation $v_p \sim tg$, where g is the gravitational force field generated by mass density fluctuations and $t \sim H_0^{-1}$ is the age of the universe as the only possible time scale. Peculiar velocity data yield a bulk peculiar velocity of $v_p \sim 300 \text{ km s}^{-1}$ for the sphere of radius $R \sim 100 \text{ Mpc}$ around us. This corresponds to a gravitational potential $U_{100}^{LS} \sim v_p R H_0 \approx (5 \times 10^{-3} c)^2 \sim 50 U_{MW}$ where U_{MW} is the gravitational potential depth associated with the MW. Note that $U_{100} = \mathcal{O}(10^{-5})c^2$ is of the same order of magnitude as the potential fluctuations inferred from the temperature fluctuations in the cosmic microwave background (Bennett et al. 1994). Since the gravitational time lag is proportional to the line of sight integral over the potential, the contribution from LSS greatly exceeds that of the MW. It also dominates the delay due to the passage of photons through individual clusters of (Zhang 2016).

3. THEORETICAL ESTIMATE BASED ON Λ CDM

We provide a statistical estimate of the shift in the gravitational time lag, Δt_{gra}^{LS} , due to LSS in frame work of the Λ CDM model (Planck Collaboration et al. 2015).

We are interested in the rms value, $\sigma = \langle (\Delta t_{gra}^{LS})^2 \rangle^{1/2} = \Delta\gamma \tilde{\sigma}$ where the averaging is over all directions. We express $\tilde{\sigma}^2 = \sum_l \frac{2l+1}{4\pi} C_l$ in terms of the angular power spectra, C_l , and write (Nusser et al. 2013)

$$C_l = \frac{2}{\pi c^6} \int dk k^2 P_U(k) \left| \int_{r_1}^{r_2} dr D[t(r)] j_l(kr) \right|^2, \quad (4)$$

where P_U is the power spectrum of the gravitational potential at redshift $z = 0$. Further, we have used the linear theory result that the gravitational potential $U(\mathbf{r}, t) = (D/a)U_0(\mathbf{r}, t_0)$ where $D(t)$ is the linear growth factor (Peebles 1980). Adopting the Λ CDM cosmology, these expressions are computed numerically as a function of the redshift of the burst. The lower curve in Fig. 1 is the upper limit $\Delta\gamma < \tilde{\sigma}^{-1}$ for $\Delta t_{gra} < 1 \text{ s}$ between photons emitted by a burst at redshift z . For comparison, the upper curve represents the limit obtained by considering the MW alone according to Eq. (2). The curve is obtained for $M_{MW} = 2 \times 10^{12} M_\odot$ in accordance with the mass determination from the dynamics of the Local Group (Phelps et al. 2013).

4. ACTUAL CONSTRAINTS

The expected time shift has been estimated in a statistical way. The *rms* LSS contribution is overwhelmingly greater than the MW and, therefore, we could derive stringe constraints even without an actual measurement of the LSS gravitational potential to the extragalactic burst. According to the figure, the probability that the LSS contribution at $z \sim 1$ acquires values smaller than the MW's is $10^{-4.8}$, i.e. 4.3σ rejection level. Values 200 times smaller than the MW's are rules out at the 3σ level. We derive now constraints from several bursts already considered in the literature:

- *FRB 110220*: This is the object used in Wei et al. (2015). Based on the figure, for FRB 110220 at $z \sim 0.8$ (estimated from the DM) we derive the limit

$$\begin{aligned} \gamma_{1.2 \text{ GHz}} - \gamma_{1.5 \text{ GHz}} &< 4.5 \times 10^{-11} \quad (3\sigma) \\ &< 2.8 \times 10^{-12} \quad (2\sigma). \end{aligned} \quad (5)$$

for $\Delta_{gra} < 1 \text{ s}$. Since the observed arrival times of photons depends on frequency as expected from the propagation of radio waves in an ionized medium, we infer that deviations from EEP make a subdominant contribution to the observed lag. This gives us confidence in the DM based redshift estimate and in adopting the observed lag of 1 second as an upper limit on gravitational delays.

- *FRB 150418*: Keane et al. (2016) associate this FRB with a subsequent fading radio source at the position of a galaxy at $z = 0.492 \pm 008$ (but see

Williams & Berger (2016) for a different point of view). For this redshift, Tingay & Kaplan (2016) estimate Δt_{gra} to be less than 5%-10% of the total time delay of 0.8 s. Following Tingay & Kaplan (2016), we take $z = 0.49$ and $\Delta t_{gra} < 0.04$ s to obtain the constraint

$$\begin{aligned} \gamma_{1.2GHz} - \gamma_{1.5GHz} &< 2.4 \times 10^{-12} \quad (3\sigma) \\ &< 1.4 \times 10^{-13} \quad (2\sigma). \end{aligned} \quad (6)$$

compared to their hard constraint $\Delta\gamma < 10^{-9}$.

- *GRB 090510*: The firmest constraint obtained in (Gao et al. 2015) is for GRB 090510 at $z = 0.903 \pm 0.003$ (Rau et al. 2009) and a time delay of 0.83 seconds between GeV and MeV photons. For this object we obtain the limit

$$\begin{aligned} \gamma_{GeV} - \gamma_{MeV} &< 4 \times 10^{-11} \quad (3\sigma) \\ &< 2.3 \times 10^{-12} \quad (2\sigma). \end{aligned} \quad (7)$$

- *GRB 080319B*: This GRB is at $z = 0.937$ (Vreeswijk et al. 2008) with an upper limit on the time delay of 5 seconds between eV and MeV photons. The corresponding limit we derive here is

$$\gamma_{eV} - \gamma_{MeV} < 2.3 \times 10^{-10} \quad (3\sigma)$$

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$$< 1.3 \times 10^{-11} \quad (2\sigma). \quad (8)$$

These numbers are smaller by a factor of a few 100s than the corresponding constraints obtained in (Gao et al. 2015). Future deep galaxy redshift surveys, e.g. Euclid (Laureijs et al. 2011), and peculiar velocity data will allow an actual estimation of the gravitational potential along the line of sight to some relevant transient events. This should yield robust constraints on the accuracy of EEP from events of cosmological origin. Obtaining redshifts of FRBs is the focus of intense observational activity. Thus measured redshifts, especially of repeating events are expected be available in the very near future. This would be very rewarding since FRBs offer important constraints on several aspects of deviations from standard physics such the photon mass (Bonetti et al. 2016; Wu et al. 2016), in addition to EEP.

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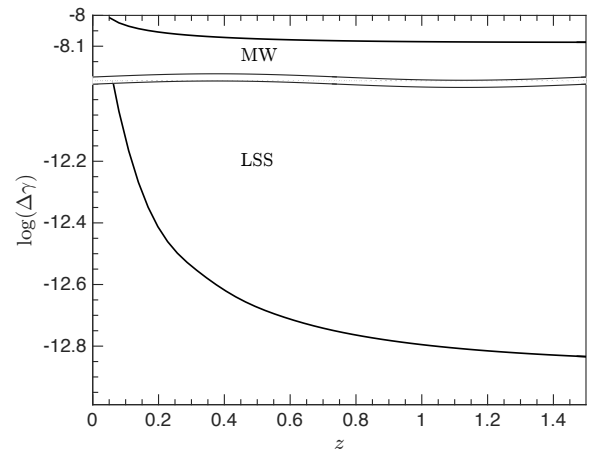


Figure 1. Upper limits on $\Delta\gamma$ as a function of redshift of the source for an assumed shift of $\Delta t_{gra} < 1$ s. Lower curve corresponds to rms value of the LSS contribution while the upper curve is the limit obtained from the MW potential. These upper limits correspond to a time lag of 1 second.

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